SYSTEMS TECHNOLOGY LABORATORY SERIES

STL-80-004

(NASA-TM-84789) ALGORITHMS FOR AUTONOMOUS STAR IDENTIFICATION (NASA) 38 p HC A03/MF A01 CSCL 09B

N82-29031

Unclas G3/61 28384

ALGORITHMS FOR AUTONOMOUS STAR IDENTIFICATION

OCTOBER 1980

NASA

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

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FOREWORD

The Systems Technology Laboratory (STL) is a computational research facility located at the Goddard Space Flight Center of the National Aeronautics and Space Administration (NASA/GSFC). The STL was established in 1978 to conduct research in the area of flight dynamics systems development. The laboratory consists of a VAX-11/780 and a PDP-11/70 computer system, along with an image-processing device and some microprocessors. The operation of the Laboratory is managed by NASA/GSFC (Systems Development and Analysis Branch) and is supported by SYSTEX, Inc., Computer Sciences Corporation, and General Software Corporation.

The main goal of the STL is to investigate all aspects of systems development of flight dynamics systems (software, firmware, and hardware), with the intent of achieving system reliability while reducing total system costs. The flight dynamics systems include the following: (1) attitude determination and control, (2) orbit determination and control, (3) mission analysis, (4) software engineering, and (5) systems engineering. The activities, findings, and recommendations of the STL are recorded in the Systems Technology Laboratory Series, a continuing series of reports that includes this document. A version of this document was also issued as Computer Sciences Corporation document CSC/TM-80/6303.

The primary contributors to this document include

Pascal Gambardella	(Computer Sciences Corporation)

Other contributors include

Raymond Byrne	(Computer Sciences Corporation)
Malcom Shuster	(Computer Sciences Corporation)
Eugene Lefferts	(Goddard Space Flight Center)
Roger Werking	(Goddard Space Flight Center)

Single copies of this document can be obtained by writing to

Keiji Tasaki
Code 582.1
NASA/GSFC
Greenbelt, Maryland 20771

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ABSTRACT

Algorithms for onboard autonomous star identification are presented. The algorithms are applicable to two types of spacecraft missions, those flown with nearly inertially fixed attitude (SMM type); and those flown with smoothly time-varying attitude (Landsat-D type).

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SECTION 1 - INTRODUCTION

One of the key objectives of NASA's Multimission Modular spacecraft (MMS) program is the autonomous onboard determination of spacecraft attitude (Reference 1). The processing of star camera data and the subsequent identification of stars are essential elements of any autonomous attitude determination system. An example of an autonomous attitude determination algorithm is shown in Figure 1-1. This memorandum provides a detailed description of a semi-autonomous star identification algorithm suitable for implementation by a microprocessor onboard the spacecraft.

The algorithm is applicable to two types of spacecraft missions, those flown with nearly inertially fixed attitude (SMM type) (Reference 2); and those flown with smoothly time-varying attitude (Landsat-D type) (Reference 3).

The onboard star identification algorithm is divided into three separate modules (Figure 1-2) which are characterized by the functions they perform. The three functions are snapshot processing (Figure 1-3), generation of a subcatalog from an onboard star catalog, and the performance of pattern matching between observed and catalog stars. A snapshot is formed of all stars present in a star camera's field of view (FOV). Using onboard-propagated spacecraft attitudes the coordinates of the stars in the snapshot are rotated into an inertial frame to facilitate identification with reference stars stored in an onboard catalog. Direct or pattern matching techniques are necessary to ensure accurate star identification. Star observations are processed one at a time through the entire system, i.e., from raw data through the completion of star identification. This processing minimizes the microprocessor core requirements.

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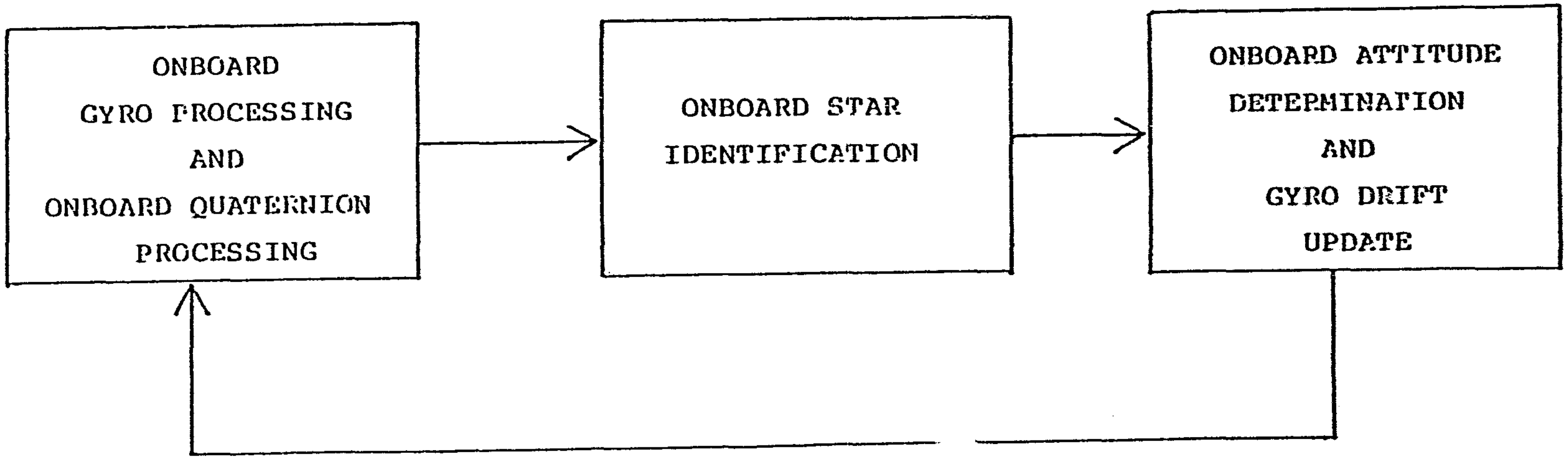

FIGURE 1-1. AUTONOMOUS ATTITUDE DETERMINATION

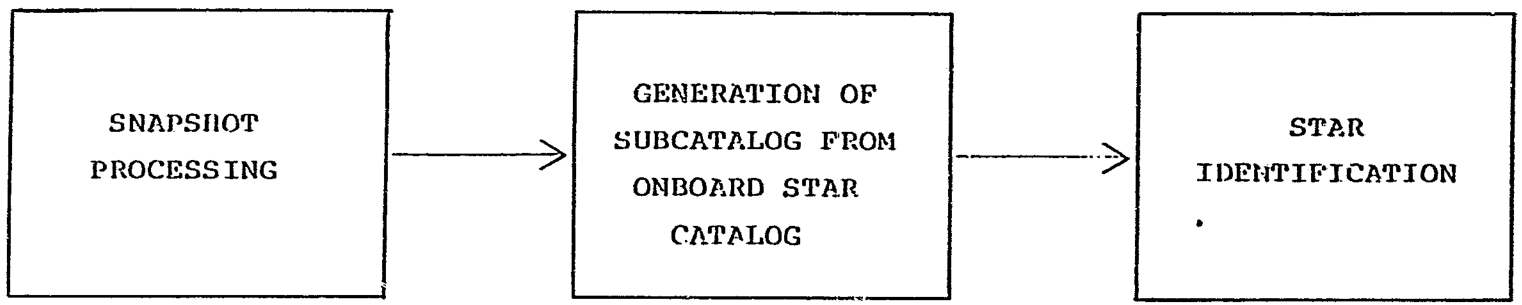

FIGURE 1-2. ONBOARD STAR IDENTIFICATION

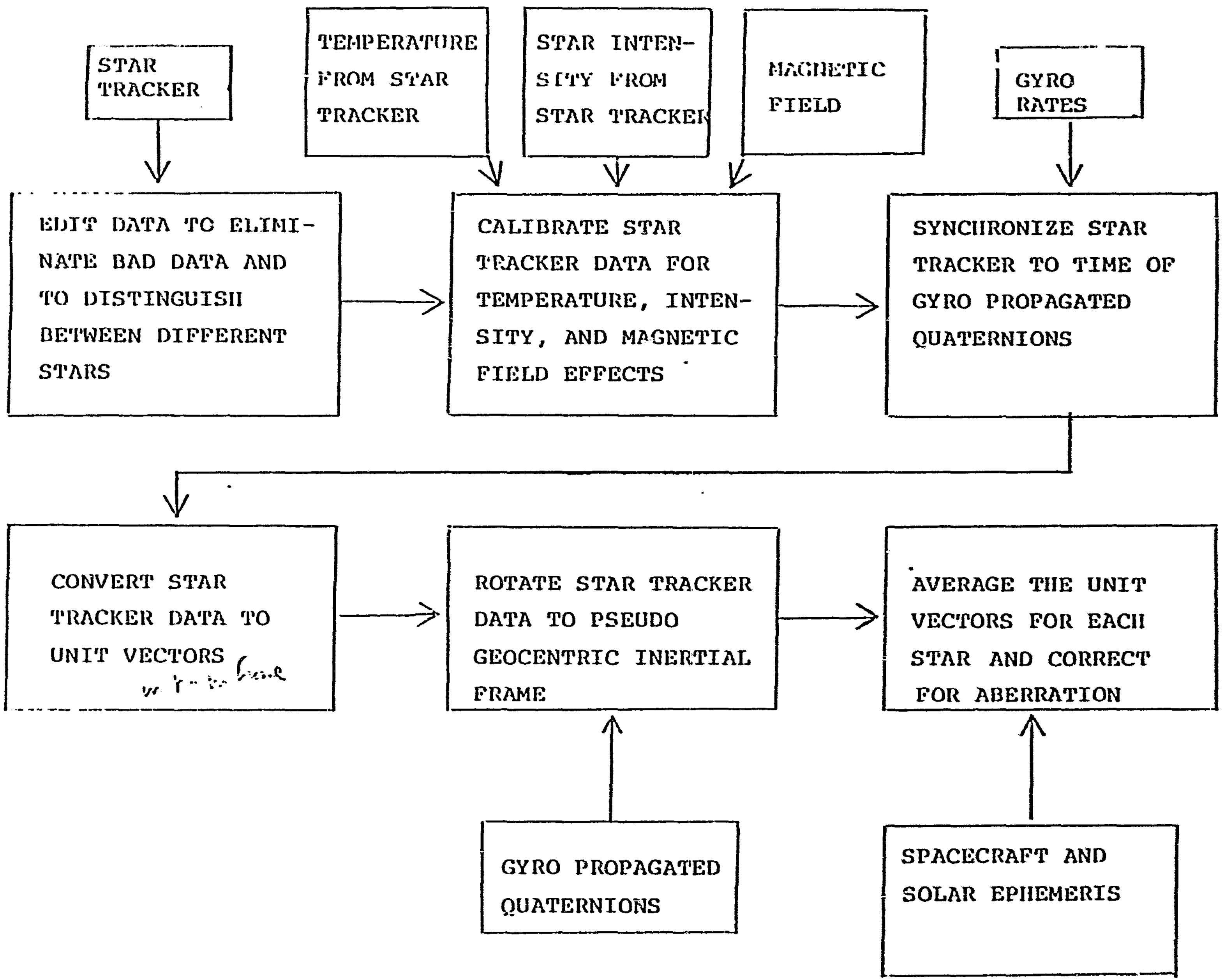

Figure 1.3. Snapshot Processing

The identified star observations and their corresponding catalog stars and other relevant data are stored in an array for access by the attitude determination system.

The onboard star identification algorithm is designed to satisfy the following general requirements (Reference 5) necessary for optimal onboard attitude determination using an onboard microprocessor. The algorithm accepts star observations directly from the star trackers, i.e., it does not assume any pre-processing. It provides for quality checking of the star observations as well as for checking of the sensor operational flags. It accepts star tracker alignments, scale factors, and a priori biases and calibration coefficients from an onboard data base. It accepts spacecraft ephemeris[1] and a star catalog from an onboard data base. It processes star tracker data and performs star identification activities in realtime. It provides star observations and corresponding identified catalog stars to an onboard attitude determination system. The onboard attitude determination system provides for onboard estimation of sensor parameters, such as gyro drift biases, whose short term instability is likely to degrade the attitude accuracy. The spacecraft can operate autonomously for a period of at least 3 days without any ground intervention. The exact period of autonomy is limited by the size of the onboard catalog.

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1 The Navstar Global Positioning System (GPS) is a possible source of the spacecraft ephemeris (Reference 6).

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SECTION 2 - SNAPSHOT PROCESSING

2.1 OVERVIEW

In this section, the operation of the Fixed Head Star Tracker (FHST) and algorithms for onboard snapshot processing are discussed. Star observations are processed one at a time through the entire system, i.e., from raw data through the completion of star identification.

2.2 COORDINATE SYSTEMS

The coordinate systems referred to in this memorandum are described in the following subsections.

2.2.1 GEOCENTRIC INERTIAL COORDINATES

The X_I, Y_I, and Z_I coordinate axes refer to the geocentric inertial coordinates (GCI), where X_I axis points to the vernal equinox; the Z_I axis points to the North Celestial Pole; and the Y_I axis points along the direction of $\hat{Z}_I \times \hat{X}_I$.

2.2.2 RIGHT ASCENSION - DECLINATION SYSTEM

The right ascension, α, is measured eastward in the plane of the celestial equator from the vernal equinox direction. The declination, δ, is measured northward from the celestial equator to the line of sight. A unit vector in the geocentric inertial frame is expressed in terms of α and δ as follows,

$$\left(\hat{r}\right)_{GCI} = \begin{pmatrix} \cos\delta & \cos\alpha \\ \cos\delta & \sin\alpha \\ \sin\delta & \end{pmatrix} \tag{2-1}$$

2.2.3 SPACECRAFT BODY FIXED REFERENCE FRAMES

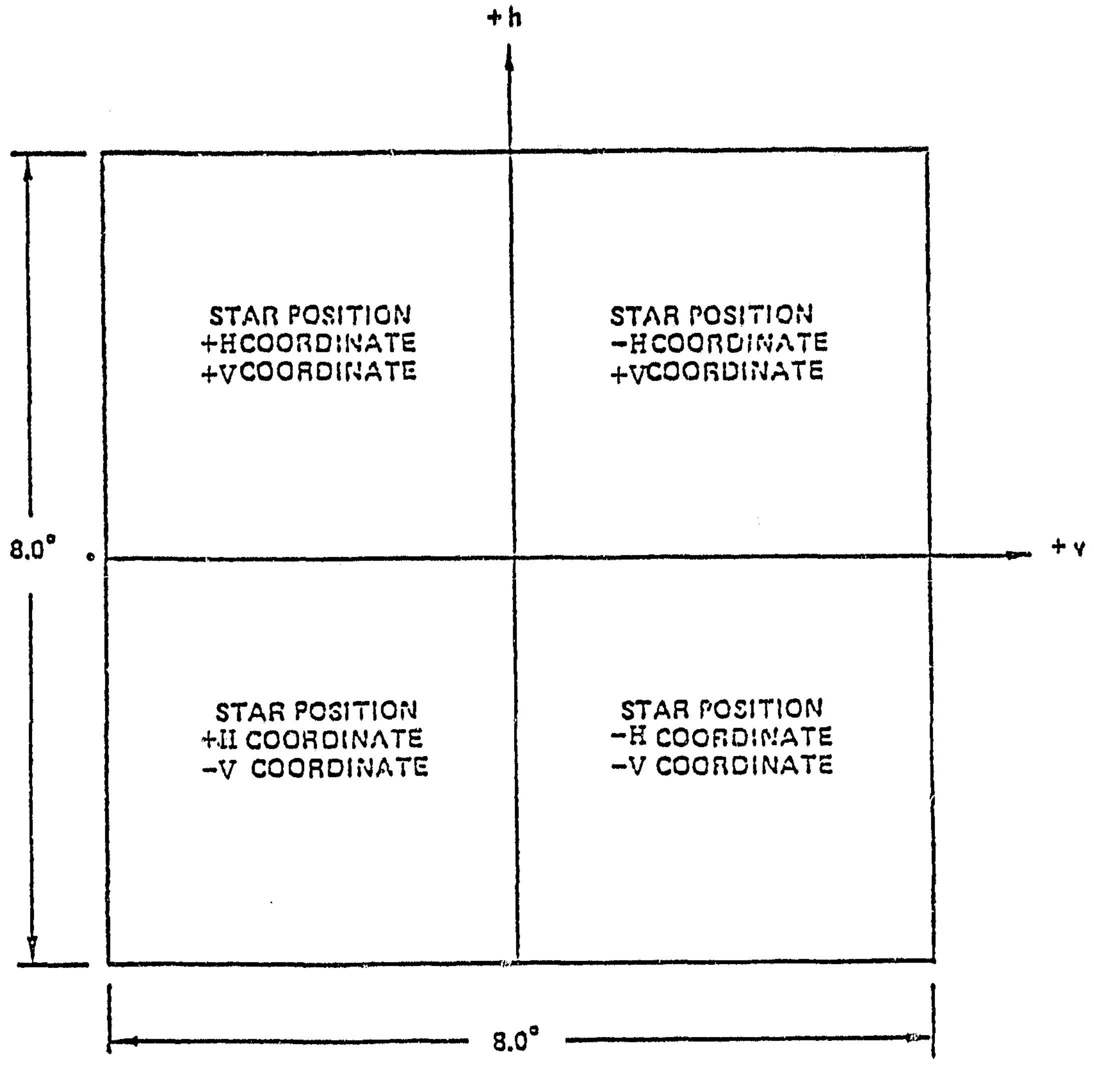
The spacecraft reference frame is fixed with respect to the structure of the vehicle. Sensor coordinate reference frames are defined by constant transformations from the spacecraft reference frame. The matrix $_T M_{SC}$ represents the transformation from the spacecraft reference frame to each of the star tracker reference frames, i = 1,2.

2.3 FHST OPERATION

The FHST detects stars and provides star position and star magnitude data. It searches for and acquires stars of visual magnitude between +5.7 and 2 (class G0V) in an 8-degree square FOV (Reference 4). It tracks the acquired star with a small tracking pattern, following the star throughout the FOV. It provides accurate two-axis position signals indicating the position of the star in the FOV. Upon command, the search mode is restarted and the next star encountered in the FOV is acquired. An independent bright object sensor (BOS) and a shutter mounted in a separate shutter housing assembly, with Sun shade attached, protect the image dissector tube from excess energy.

The FHST operates as follows: When power is supplied to the system and no other mode is commanded, the FHST automatically starts searching the total field of view (TFOV). The search scan pattern is a left-to-right, right-to-left horizontal (H) direction sweep with a staircase signal applied to the vertical (V) direction (raster pattern). Four commandable threshold levels are provided for setting the minimum sensitivity from +6.0 to +3.0 visual magnitudes. The search scan continues until the first star that exceeds the commanded threshold level is encountered. When this occurs, the star is acquired and the track scan begins. (The time required to search the TFOV does not exceed 10 seconds.)

The track scan pattern centers on the star image, and two-axis position signals are provided at the system output. If the star moves in the FOV because of small vehicle attitude changes, the track scan pattern follows and remains



Total field of view (TFOV) as viewed from inside the FHST looking out at the star field with the interface connectors facing down.

Figure 2-1. FHST Coordinate System

centered on the star image.[1] The star position is identified by a positive or negative H coordinate and a positive or negative V coordinate based on the coordinate system shown in Figure 2-1. Positive position signals in the H and V directions represent positive rotations about the h and v axes. Tracking of the same star continues until (1) it leaves the TFOV, (2) the amplitude of the signal falls below the commanded threshold, or (3) a BREAK TRACK command (Reference 4) is received from the user.

An estimate of the average number of stars in the 8 degree square FOV is provided in Table 2-1 for the SMM star trackers. This information is useful in estimating the size of the onboard catalog.

2.4 ALGORITHMS

The output of the star tracker corresponds to many sequential sightings of each different star. For a given star, one sighting is called a track point and all the sightings are referred to as a track group (Figure 2-2). Each track point is edited and calibrated to form observed star unit vectors in the spacecraft reference frame. Quaternions are formed from an initial attitude estimate and gyro data. These quaternions are used to transform the observed star unit vectors in a given track group into a common reference frame, the pseudogeocentric inertial frame (PGCI). It differs from a true inertial frame because of gyro-related and propagation errors. The track points for a given track group will not coincide in the PGCI frame due to those errors. An average PGCI unit vector for the track group is then constructed by summing the individual track point unit vectors and normalizing the result. In the PGCI frame, the individual track point unit vectors in a given track group are referred to as a clump (Figure 2-3).

[1] According to camera specifications, the camera can follow a star moving in the FOV at a rate of 0.3 degree/second or less.

Table 2-1. FHST Threshold Settings

	FHST 1 (S. No. 002)		FHST 2 (S. No. 001)	
Setting	Actual Threshold	Average No. of Stars in FHST TFOV	Actual Threshold	Average No. of Stars in FHST TFOV
3	3.981	0.85	3.81	0.70
4	4.664	1.80	4.50	1.50
5	5.731	5.80	5.54	4.70
6	6.552	14.28	6.44	12.63

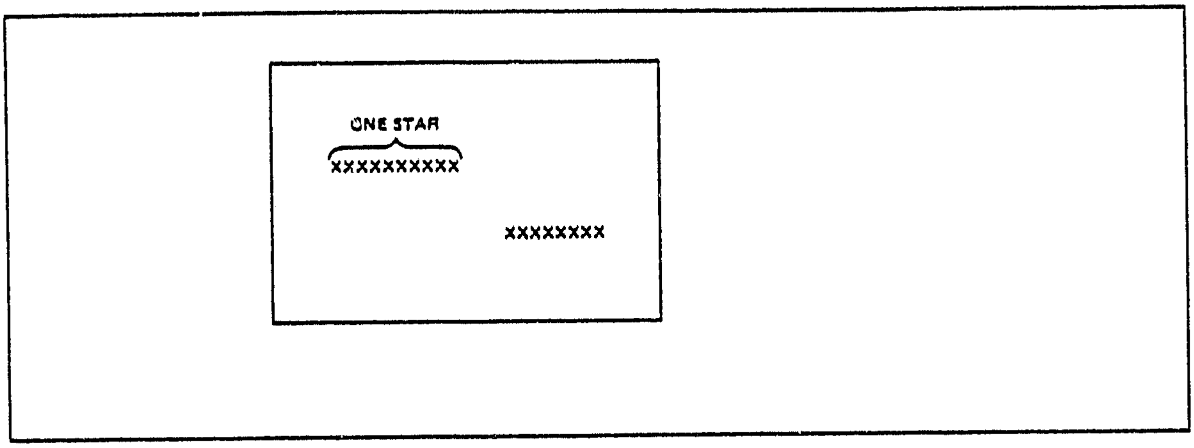


Figure 2-2. Observations in Star Tracker FOV

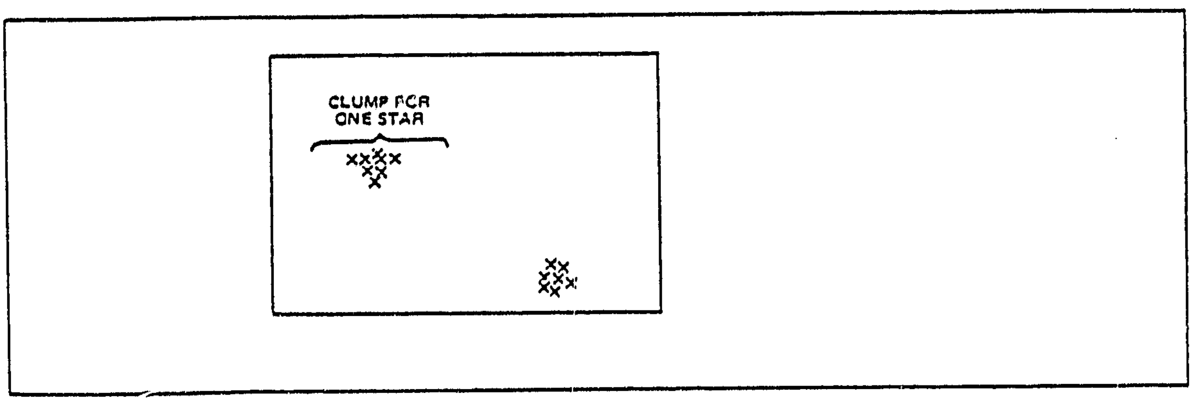


Figure 2-3. Transformation of Star Tracker Observations to PGCI Frame

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The steps involved in processing data from a single star tracker are shown in Figure (1-3). Star position data, temperature, and star intensity are output from the star tracker. The magnetic field is either internally computed using spacecraft ephemeris data or is provided by an onboard magnetometer. Gyro rates and gyro propagated quaternions are provided by an external gyro processing subsystem. The Solar ephemeris is stored or computed onboard.

2.4.1 DATA EDIT

Tests are provided to ensure the star tracker output data is constrained by minimum and maximum tolerances, the track groups for different stars are distinguishable, and bad data is eliminated. Data is collected during a time τ specified by the user. Star tracker position output H and V, temperature output T and intensity output I are tested as follows to verify they fall within minimum and maximum tolerances,

$$\begin{aligned} H_{MIN} &\le H_O \le H_{MAX} \\ V_{MIN} &\le V_O \le V_{MAX} \\ T_{MIN} &\le T \le T_{MAX} \\ I_{MIN} &\le I \le I_{MAX} \end{aligned} \tag{2-2}$$

where H_{MAX}, H_{MIN}, V_{MIN}, V_{MAX}, T_{MIN}, T_{MAX}, I_{MIN}, and I_{MAX} are user defined tolerances. If H_i, V_i, $i \ge 1$, represent a sequence of star camera track points, then track points satisfying

$$\begin{aligned} \left| H_{i+1} - H_i \right| &< K_1 \\ \left| V_{i+1} - V_i \right| &< K_2 \end{aligned} \tag{2-2}$$

are considered to belong to the same star, where K_1 and K_2 are user specified constants. The number of track points collected for each star satisfies minimum and maximum limits. Track points are edited from the beginning and end of each track group to eliminate transient effects. Track groups are discarded if they overlap in time a gyro gap of duration t_g seconds or greater. Track points are discarded if they do not have at least one corresponding intensity between the first and last valid track point.

2.4.2 CALIBRATION OF FHST

This subsection describes the FHST calibration procedure. The form of the calibration equations (Reference 4) is as follows:

$$
\begin{aligned}
f_1(H,V,X) = {} & C_1 + C_2V + C_3H + C_4X + C_5V^2 + C_6VH + C_7VX + C_8H^2 \\
& + C_9HX + C_{10}X^2 + C_{11}V^3 + C_{12}V^2H + C_{13}V^2X \\
& + C_{14}VH^2 + C_{15}VHX + C_{16}VX^2 + C_{17}H^3 + C_{18}H^2X + C_{19}HX^2
\end{aligned}
$$

where

H = horizontal axis output in counts

V = vertical axis output in counts

X = physical parameter as defined below

$f_1(H, V, X)$ = H value corrected for X

C = calibration coefficients corresponding to H value corrections (TBD)

The expression $f_2(H, V, X)$ for the V value corrected for X is of the same form as $f_1(H, V, X)$ except for different calibration coefficients C.

Five separate applications of the above equation are necessary for each axis. The first application is a flat-field temperature calibration; X is the temperature in volts. The second application is for intensity, with X being the star intensity in volts. The third application has X equal to the magnetic field along the star tracker h axis in gauss; and the fifth application has X equal to the magnetic field along the star tracker v axis. The values of C_i for all of these calibrations are TBD. For particular attitude accuracy requirements, a study should be initiated to determine how these equations can be simplified to minimize the number of calibration coefficients. For example, the magnetic field contribution on the SMM mission is less than 1 arc second.

2.4.3 SYNCHRONIZATION OF FHST DATA TO GYRO PROPAGATED QUATERNIONS

It is necessary to synchronize the calibrated FHST position output H and V to the gyro propagated quaternions; the quaternions are used to rotate the star data to the PGCI frame. The quaternion $Q(t_i)$ represents a rotation from the PGCI frame to the spacecraft reference frame at time t_i. The gyro processing system supplies, both the gyro rates $W(t_i)$ in the spacecraft body frame, and the quaternions. The quaternions and gyro rates are available at a lower frequency than the star data. An algorithm to synchronize the FHST data to the quaternion is described in this section.

The star unit vector in the tracker frame is defined by

$$\hat{u} = \begin{pmatrix} u_x \\ u_y \\ u_z \end{pmatrix} = \begin{pmatrix} \cos\theta_V \cos\phi_H \\ -\sin\theta_V \cos\phi_H \\ \sin\phi_H \end{pmatrix} \qquad (2\text{-}5)$$

where

$$\theta_V = V\beta_1$$
$$\phi_H = H\beta_2$$

and β_1 and β_2 are scale factors. Suppose star tracker position output occurs at time t' where $t_i \leq t' \leq t'_{i-1}$. The average gyro rate is computed by

$$W_{AVG} = \tfrac{1}{2} (W_i + W_{i-1})$$

and converted to the star tracker reference frame,

$$\left[W_{AVG}\right]_T = T^M{}_{SC}\, W_{AVG}$$

Synchronized star tracker output can be calculated from

$$\begin{pmatrix} 1 \\ -\theta'_V \\ \phi'_H \end{pmatrix} = \begin{pmatrix} 1 \\ -\theta_V \\ \phi_H \end{pmatrix} + \left[W_{AVG}\right]_T \Delta t \qquad (2\text{-}6)$$

where $\Delta t = -t' + t_{i-1}$, if $\check{t}' < \frac{1}{2}(t_i - t_{i-1})$,

synchronizing θ'_V and ϕ'_H to $Q(t_{i-1})$

and $\Delta t = -t' + t_i$, if $t' \geq \frac{1}{2}(t_i - t_{i-1})$

synchronizing θ'_V and ϕ'_H to $Q(t_i)$

The synchronized star unit vector $\hat{u}'$ is then obtained by inserting θ'_V and ϕ'_H into equation (2-6).

2.4.4 ROTATION OF STAR TRACKER DATA TO PGCI REFERENCE FRAME

The average star vector is transformed to the PGCI reference frame is given by

$$\vec{u} = \frac{1}{n} \sum_{k=1}^{n} A_Q^T(t_k)\, {}_T M_{SC}^T\, \hat{u}_T^{(k)} \qquad (2\text{-}7)$$

where

$\hat{u}_T^{(k)}$ = synchronized track point unit vectors in the tracker reference frame, $1 \leq k \leq n$

t_k = the time of the k^{th} track point in the track group, $1 \leq k \leq n$

$A_Q(t_k)$ = the matrix corresponding to the quaternion $Q(t_k)$.

It is necessary to correct the observed average star unit vectors for aberration effects. This correction can be of the order of 20 arc-seconds. The complexity of this calculation is considerably reduced if it is applied to the observed star unit vectors rather than to the catalog unit vectors. In the latter case, the catalog stars in right ascension-declination reference frame would have to be converted to star unit vectors, corrected for aberration and then reconverted back to right ascension-declination reference frame (see Section 3). In addition, the correction would have to be applied to all the catalog stars which serve as identification candidates for the observed star. The vector $\vec{u}$ is unitized to $\hat{u}$ and corrected for aberration as follows:

$$\hat{u}_c = (\hat{u} - T\hat{V}) / \|\hat{u} - T\hat{V}\| \qquad (2\text{-}8)$$

with

$$\vec{V} = \vec{V}_E + \vec{V}_{SC} \qquad (2\text{-}9)$$

and

$$T = \frac{\|\vec{V}\|}{c} \qquad (2\text{-}10)$$

where $\vec{V}_E$ is velocity vector of the Earth around the Sun in the GCI reference frame, $\vec{V}_{SC}$ is the velocity of the spacecraft relative to the Earth and c is the speed of light. The velocity $\vec{V}_E$ is determined from the Solar ephemeris which must be stored or computed onboard.

The vector $\hat{u}_c$ is converted to right ascension and declination using the equations

$$\alpha = \text{arc tan } (u_y/u_x) \qquad (2\text{-}11)$$
$$\delta = \text{arc sin } (u_z)$$

SECTION 3 - ONBOARD STAR CATALOG

The contents, order, size, and accessing of the onboard star catalog are discussed. The star catalog contains the right ascenstion α, declination δ, and magnitude of each star. The star catalog is ordered by right ascension into η (nominally 360) subcatalogs with stars in each subcatalog ordered by declination. The size of the onboard star catalog is limited by the available memory in the onboard microprocessor. The period of spacecraft autonomy depends on the size of the onboard catalog. An estimate of the average number of new stars per day for FHST1 (see Table 2-1) for Landsat-D and SMM in nominal mission mode is given in Table 3-1. Suppose FHST1 and FHST2 view different regions of the celestial sphere in one week, then an estimate of the total number of stars viewed by both trackers in one day and one week based on this assumption appears in Table 3-2.

The storage requirements for each star in the catalog is 12 bytes. Storage estimates for the Landsat-D and SMM missions appear in Table 3-3. To minimize star tracker processing in the attitude determination system, it may be advantageous to additionally store the star catalog unit vectors in the GCI reference frame. This additional storage would double the star catalog storage.

For each observed star, the onboard catalog is accessed and a subcatalog is generated for use on star identification. Suppose α_0 and δ_0 are the right ascension and declination, respectively, of the observed star. One or two of the 360 subcatalogs are accessed to cover the interval

$$\alpha_0 + \Delta_1 \geq \alpha \geq \alpha_0 - \Delta_1 \qquad (3-1)$$

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Threshold Setting	Average Number of New Stars Per Day in FHST 1	
	Landsat-D	SMM
3	2.39	0.11
4	5.06	0.22
5	16.3	0.73
6	40.15	1.79

Table 3-1. Average Number of New Stars Per Day in One Star Tracker for Landsat-D and SMM

Threshold Setting	Average Number of Stars Viewed by Both Star Trackers			
	Landsat-D		SMM	
	one day	one week	one day	one week
3	38	67	2	3
4	81	142	4	7
5	261	457	12	21
6	643	1125	28.6	50

Table 3-2. Average Number of Stars Viewed by Both Trackers for Landsat-D and SMM

Period	Storage (K bytes) (FHST Threshold Setting = 6)	
	Landsat-D	SMM
one day	8	0.4
one week	15	0.8
entire catalog	64	64

Table 3-3. Storage Requirement Estimates of the Onboard Star Catalog for Landsat-D and SMM

where Δ_1 is a mission dependent tolerance (nominally 0.1 degree). Only one subcatalog need be accessed if the subcatalogs overlap in right ascension by Δ_1. The equation

$$T(\alpha,\delta) = (\alpha - \alpha_0)^2 + (\delta - \delta_0)^2 \qquad (3\text{-}2)$$

is applied to all stars in the subcatalog which satisfy

$$\delta_0 + \Delta_2 \geq \delta \geq \delta_0 - \Delta_2 \qquad (3\text{-}3)$$

If $|\alpha - \alpha_0| > \pi$ or $|\delta - \delta_0| > \pi$ in Equation (3-2), replace them with $2\pi - |\delta - \delta_0|$ or $2\pi - |\alpha - \alpha_0|$, respectively.

Catalog stars which satisfy

$$T(\alpha, \rho) \leq \varepsilon \qquad (3\text{-}4)$$

where ε is a constant tolerance are considered candidates for the observed star (see Section 4).

SECTION 4 - STAR IDENTIFICATION

Stars are identified primarily by a direct matching technique. For star identification to be considered successful, at least n (nominally 3) stars must be matched to catalog stars within a time t_I. A pairwise matching technique is employed when successful star identification is not obtained by exclusive use of the direct matching technique. The output of the star identification algorithm is the observed and catalog star positions in a format consistent with the input to the attitude determination algorithms. The time associated with the midpoint of the track group for each observed star is also output. To achieve attitude accuracy requirements it is necessary to compute an attitude using stars from each tracker. A star tracker observability error analysis for SMM is presented in the Appendix. The star identification algorithm presented here can accept star observations from both star trackers. The consequence of using stars from both star trackers is an enlarging of the accessed star catalog (see Section 3).

For successful star identification by direct match there must be only one star in an observation window centered on the observed star. For an attitude error of 30 arc-seconds, the observation window size is typically 0.1 degree square as on SMM. Assuming a uniform distribution of stars in the celestial sphere of density ρ , the probability of two or more stars in an observation window of area A is should be

$$P(\rho\ , A) = \left[1 - (1 + \rho A)\ \exp\ (-\rho A)\right] / \left(1 - e^{-\rho A}\right) \quad = .003$$

This probability is 0.011 using a consecutive estimate of the density, $\rho = 0.6\ (\text{degree})^{-2}$, and a window size of 0.1 degree square. Although this probability is small, it's large enough to include pairwise matching in the algorithm.

Each star catalog candidate for an observed star is first subject to an intensity test. The stellar magnitude of the observed star is given by

$$M_o = -a \log_{10} I + b$$

where I is the tracker output intensity in volts and a and b ($a > o$, $b > o$) are constants which depend on the particular star tracker used. Each star catalog candidate must satisfy

$$M_c < F(M_o)$$

where M_c is the catalog magnitude and F (TBD) is a function of Mo. The function F is designed to compensate for the star tracker decreasing intensity sensitivity (Reference 7) as the magnitude increases.

After the intensity test is performed (see Figure 4-1), each observed star could have no catalog star candidate, one catalog star candidate or more than one catalog star candidate. If the observed star has no candidates, it is rejected. If there are k or more successive stars with no candidate, the observation window is enlarged. If the observed star has one candidate, it is placed in a storage area of tentatively identified stars. When there are n tentatively identified stars within a time t_I, the n stars are considered identified and placed in a storage area of identified stars. If the observed star has more than one candidate, then the pairwise matching technique is invoked. Suppose the observation with unit vector $\hat{O}$ has s candidates with unit vectors $\hat{C}_i$ $(1<i<s)$. Define the function H by

$$H(\hat{C}_i) = \arcsin \|\hat{O} \times \hat{O}_I\| - \arcsin \|\hat{C}_i \times \hat{C}_I\|$$

where $\hat{O}_I$ and $\hat{C}_I$ are the observation and catalog unit vectors, respectively, of a previously identified star. The candidate $\hat{C}_i$, which minimizes H, is matched with the observation. This algorithm is summarized in Figure 4-1.

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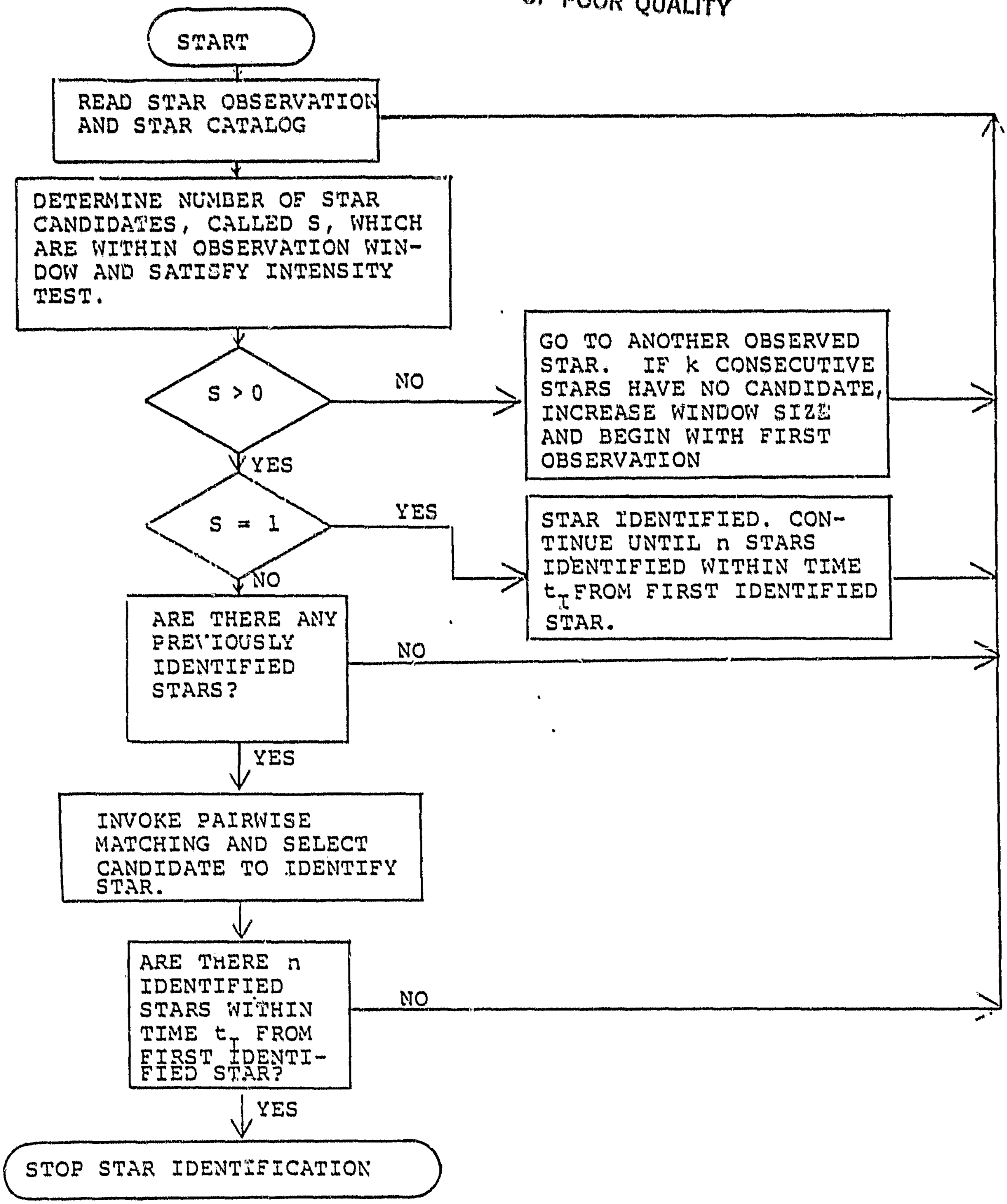

Figure 4-1. Star Identification

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APPENDIX - STAR TRACKER OBSERVABILITY ERROR ANALYSIS FOR SMM

This appendix computes the attitude error as a function of the angular distance between two star unit vectors.

This computation determines star tracker observability. This is defined as the attitude error corresponding to the relative position of the star tracker boresights.

The result and consequences of the calculation are presented; the derivations are given in Reference 7. Let one star unit vector lie along the x-axis (see Figure A-1) and the other star unit vector lie in the x-y plane at an angle θ from the first star. The attitude error about the x-axis is

$$\Sigma = \frac{(\sigma_2^2 + \sigma_1^2 \cos^2\theta)^{1/2}}{\sin\theta} \quad \text{(A-1)}$$

where σ_2 is the star tracker measurement error where i = 1 refers to the star along the x-axis and i = 2 refers to the other star. As θ approaches zero, Σ diverges, indicating a loss of observability about the x-axis. As θ approaches 90 degrees, $\Sigma = \sigma_2$, indicating complete observability about the x-axis.

A plot of the attitude error Σ as a function of the angle θ between the stars is given in Figure A-2. In this plot σ_1 is set equal to σ_2 to illustrate the observability effect described above.

The star tracker has a 8-degree by 8-degree field of view. If both stars are in one tracker, the range of θ is $0 \leq \theta \leq 8$ degrees. The boresights of the two star trackers on SMM are separated by 73 degrees. If one star is in each tracker, the maximum and minimum θ are 81 degrees and 65 degrees, respectively. The attitude error corresponding to these star configurations is given in Table A-1 with $\sigma = \sigma_1 = \sigma_2$.

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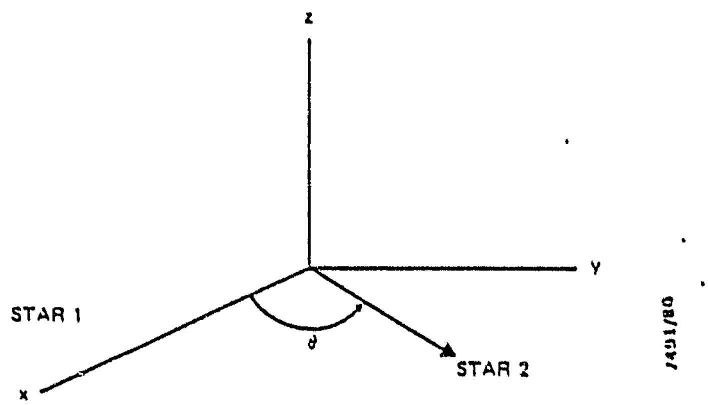

Figure A-1. Star Unit Vectors

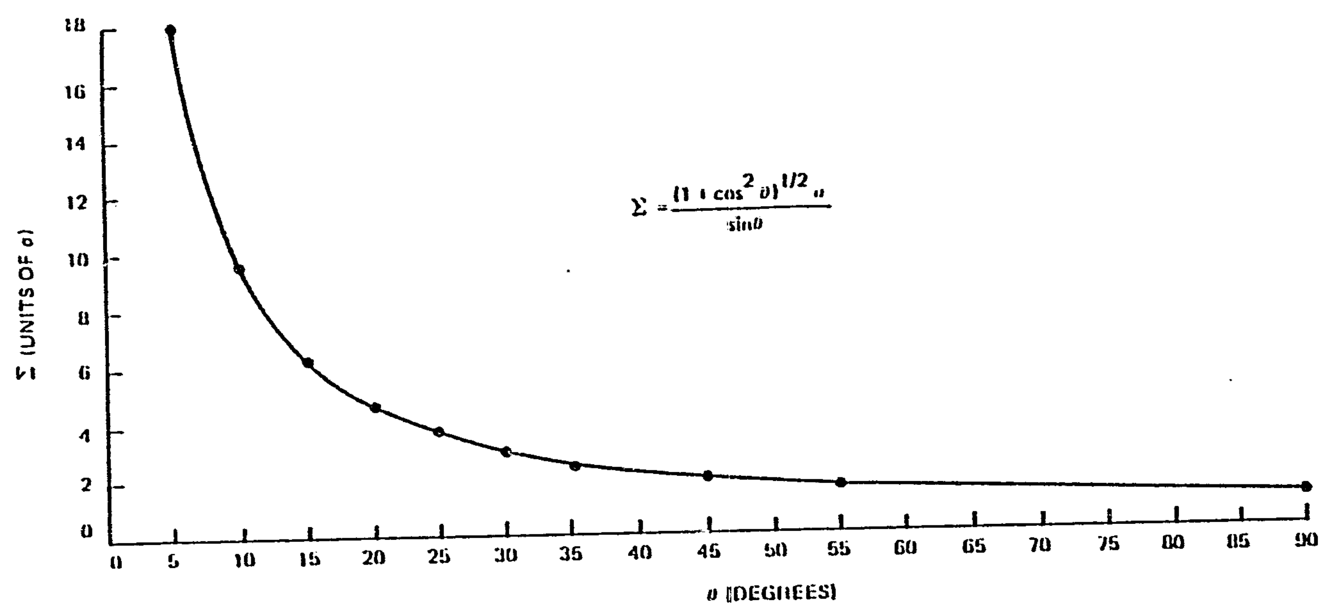

Figure A.2 Plot of the Attitude Error Σ as a Function of the Angle θ Between the Stars

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If both stars are in one tracker, the attitude error is an order of magnitude or larger than the star tracker measurement error. However, if there is a star in each tracker, the observability effect simply corresponds to the addition of from 0.4 arc-second to 4 arc-seconds to the star tracker measurement error.

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Table A-1. Attitude Error for Stars in the Star Trackers

CONFIGURATION	θ (DEGREES)	Σ/σ	Σ WITH σ = 20 ARC-SECONDS
BOTH STARS IN ONE TRACKER	0	DIVERGES	DIVERGES
	8	10.1	202 ARC-SECONDS
A STAR IN EACH TRACKER	65	1.20	24.0 ARC-SECONDS
	81	1.02	20.4 ARC-SECONDS

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